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The influence of the chemical composition, including harmful and undesirable impurities, on the properties of spring steels

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Abstract: The role of various alloying elements in improving the mechanical properties of steels used for the manufacture of springs and springs is considered. The influence of carbon, silicon, manganese, chromium, nickel and vanadium on the elasticity, strength and resistance to relaxation of spring steels is investigated. The correct selection of alloying elements and heat treatment makes it possible to increase the yield strength and elasticity, resistance to small plastic deformations and wear resistance of steels. Special attention is paid to the role of silicon, manganese and vanadium, which, along with other elements, contribute to improving hardenability, prevent decarburization and provide resistance to cracking during deformation.

Keywords: hardenability, alloying elements, silicon, chromium, vanadium

1. Introduction

The steels used for the manufacture of springs must have high resistance to small plastic deformations, endurance limit and resistance to relaxation, while providing sufficient ductility and viscosity. To achieve these properties, steel must contain more than 0.5% carbon and undergo heat treatment such as quenching and tempering, or deformation hardening.

Alloying of steels allows to increase the tempering temperature, which helps to avoid the development of irreversible tempering brittleness. This, in turn, contributes to the combination of high resistance to small plastic deformations with good ductility and viscosity [1]. Alloy steels containing 1.5–2.8% silicon, 0.6–1.2% manganese, 0.2–1.2% chromium, 0.1–0.25% vanadium, 0.8–1.2% tungsten and 1.4–1.7% nickel are often used for the manufacture of springs and springs. These elements improve the hardenability, increase the resistance to relaxation and the elastic limit of steel [1]. Alloying elements also affect the decarbonization process by changing the rate of carbon diffusion and the thickness of the decarbonized layer, as well as affect the temperature of alpha-gamma transformation and carbon activity [2].

2. Research Methodology

2.1. Influence of chemical composition

In industry, siliceous steels such as 50Si2, 55Si2, 60Si2, 60Si2CrV, 65Si2V are most often used. ***Silicon*** in the composition of these steels increases hardenability, slows down the decay of martensite during tempering and significantly strengthens ferrite. Due to this, steels 50Si2, 55Si2 and 60Si2 have high yield strength and elasticity, which provides excellent performance properties. However, siliceous steels are prone to graphitization at a silicon content above 2.5% and to decarburization during hot processing, which can reduce the endurance limit [3, 4]. Additional alloying of siliceous steels with elements such as chromium, manganese, tungsten and nickel increases calcination and reduces the tendency to decarbonization, graphitization and grain growth when heated [1].

Carbon, which is the main alloying element in steel, dissolves in the crystal lattice, although its solubility in the iron matrix is low. In the ferritic matrix, carbon saturation is achieved with a minimum content of alloying elements. Dissolved carbon reduces the modulus of elasticity of steel as the content of alloying elements increases [5]. If the carbon concentration exceeds the saturation level, excess carbon precipitates in the form of cementite, whose modulus of elasticity is about 170 GPa [6].

The effect of dissolved alloying elements such as *rhenium, cobalt, chromium, iridium, ruthenium, silicon, manganese, nickel, rhodium* and *platinum* on the modulus of elasticity of steel is illustrated in Figure 1 [7]. A slight increase in the modulus of elasticity is observed with an increase in the content of rhenium, cobalt or chromium.

The alloying mechanism, which affects the modulus of elasticity of steel, operates in two directions. First, the inclusion of atoms of alloying elements with radii different from the radius of iron in the iron (Fe) crystal lattice changes the interatomic distances. This, in turn, affects the modulus of elasticity, since it is defined as the second derivative of potential energy with respect to interatomic distances. Secondly, doping changes the distribution of electrons in the material, which also affects the modulus of elasticity. These two mechanisms can either enhance or compensate each other, depending on the properties of the alloying element and its position in the periodic table of elements [8].

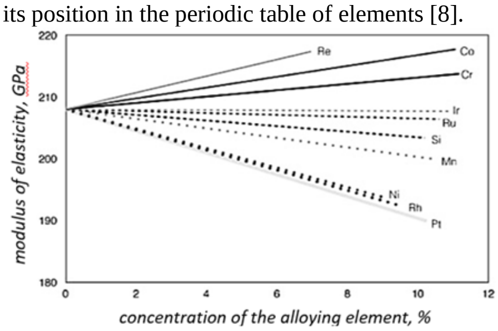

Fig. 1. The effect of alloying elements on the modulus of elasticity of steel [8]

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Manganese (Mn) plays an important role in stabilizing the γ-Fe (austenite) phase, increasing the stability of austenite and reducing the critical quenching rate. In the ferritic phase, manganese increases the tensile strength and yield strength, especially at a carbon content of 0.1 to 0.5%. However, it reduces the ductility and toughness of steel. Manganese also improves wear resistance and elasticity, which makes it an important element for alloying structural, spring-spring and wear-resistant steels. In some cases, manganese is used as a more affordable and inexpensive substitute for nickel [9].

Studies conducted by Wada and his colleagues [10-12] have shown that manganese reduces the carbon activity coefficient in austenite, which slows down carbon diffusion. Unlike manganese, silicon (Si) has the opposite effect, increasing the carbon diffusion coefficient in austenite [13].

Alloying steel with manganese, like many other elements, leads to improved technological and operational characteristics only in combination with proper heat treatment. Without heat treatment, alloying does not bring significant improvements, and the cost of the process may not be justified [9].

Chromium (Cr) is one of the most common alloying elements. It increases the strength, hardness and corrosion resistance of steel, although it may slightly reduce its ductility. The high chromium content makes the steel stainless and keeps its magnetic properties stable. Chromium also affects the rate of scale formation and reduces the tendency to decarburization by reducing the rate of carbon diffusion [9].

Vanadium (V) is added to steel to improve its mechanical properties and increase wear resistance. By forming carbides and nitrides, vanadium promotes grain grinding and increases the hardness and toughness of steel [9].

Vanadium is one of the key alloying elements used in spring-loaded steels to ensure a homogeneous and finely dispersed grain structure. Its addition significantly affects a number of processes occurring during the heat treatment of steel. Firstly, vanadium contributes to the grinding of microstructure grains, which significantly improves the mechanical properties of steel, including strength and toughness.

One of the important effects of vanadium is its ability to control processes in the lower part of the austenitic region. It slows down the growth of austenite grains, stabilizes the structure of steel during thermomechanical processing and increases the recrystallization temperature. The effect of vanadium on γ-α transformations provides a more stable microstructure and increases the mechanical characteristics of steel.

From the point of view of the electronic structure, vanadium does not possess p electrons, but has unfilled d orbitals, which leads to a decrease in the thermodynamic activity of carbon during alloying of steel. This change contributes to the formation of highly dispersed vanadium compounds such as carbides, nitrides and carbonitrides. These compounds, having a rounded shape, are evenly distributed along the grain boundaries, preventing their growth and contributing to the hardening of steel [14].

With a vanadium content ranging from 0.001% to 0.10%, it effectively reduces the size of steel grains, delaying their growth during recrystallization at high temperatures. This makes vanadium a valuable element in the composition of steels used for springs and springs, where high strength, wear resistance and stability of mechanical properties are important.

Additional alloying of steel with *chromium, vanadium* and *nickel* has a complex positive effect on its properties. Firstly, such alloying reduces the critical cooling rate, which improves the hardenability of steel, ensuring a more uniform formation of a solid and durable structure throughout the entire volume of the material.

Carbide-forming elements such as ***chromium*** and ***vanadium*** play an important role in preventing decarbonization of springs when heated before quenching, which is especially important for maintaining the surface properties and overall strength of the product. Vanadium, in turn, additionally contributes to an increase in the strength of steel due to the formation of fine carbide particles of the MS type based on VC. These carbides are formed during the decomposition of martensite during tempering and effectively harden steel, increasing its endurance and relaxation resistance.

Nickel has a positive effect on carbon activity and accelerates its diffusion in austenite, which improves the processes associated with heat treatment of steel. Although nickel has virtually no effect on the rate of scale formation, it contributes to the rapid formation of strong metal intermediate layers, which protects the steel from further oxidation.

In addition, nickel reduces the temperature of α–γ transformation, which reduces the tendency of steel to decarbonize, especially during high-temperature processing. It is important to note that the addition of nickel in an amount of 0.05–0.30% neutralizes the negative effects of copper, which is present as an impurity that can cause cracks to form on the surface of steel during hot rolling. Nickel also helps to absorb gases such as hydrogen, which prevents the formation of gas bubbles in ingots and reduces the likelihood of cracks along grain boundaries in the case of coarse-grained steel structure.

2.2. The effect of harmful and undesirable impurities

The high ***sulfur*** content in steel (up to 0.035%) has a negative effect on the crack resistance of finished springs. This is due to the formation of sulfide nonmetallic inclusions along grain boundaries. During hot deformation in the temperature range from 950°C to 1200°C, they contribute to the formation of cracks and ruptures. Therefore, the sulfur content in steels for highly loaded springs is limited to 0.025% [15]. Sulfur also globulates sulfide inclusions and participates in the formation of the plasticity level of steel, contributing to the formation of chips during machining [14].

Phosphorus is an unavoidable impurity in steel that settles along grain boundaries, reducing impact strength and leading to brittle fracture due to weakening of intergranular bonds. Therefore, the phosphorus content is limited to 0.025 wt.% [16]. During quenching and tempering, phosphorus forms junctions with elements such as chromium or manganese along the boundaries of former austenitic grains. This leads to a decrease in adhesion along grain boundaries and intercrystalline embrittlement, which has an extremely negative effect on strength and resistance to fatigue load in air. These effects have an even more negative effect on achieving high tensile strength and hardness. In order to simultaneously achieve high tensile strength, high hardness, as well as good air fatigue strength and corrosion resistance, the phosphorus content in spring steel should be as low as possible, not exceeding 0.015%, preferably 0.010%.

Microalloying with ***copper*** is based on its ability to crystallize last and concentrate along grain boundaries, reducing the likelihood of overheating and increasing the ductility of steel. In addition, copper increases corrosion resistance, although its effect becomes noticeable only at concentrations above 0.15%. However, if the copper content exceeds 0.20%, brittle copper phases can lead to cracking of grain boundaries during deformation. Copper is a hardening element in the form of a solid solution that can be added to steel along with other elements that increase its strength and hardness. Since copper does not combine with carbon, it strengthens steel without forming large and hard carbides, which can reduce fatigue strength in air [17].

The ***oxygen*** content should be from trace amounts to 0.0020%. Oxygen is an unavoidable impurity in steels, which, in combination with deoxidizers, can form large, solid and irregularly shaped inclusions or smaller but longer accumulations that negatively affect the fatigue strength in air. These effects, in particular, reduce tensile strength and hardness. To achieve a balance between high tensile strength, hardness and fatigue strength both in air and in aggressive environments, the oxygen content in steel should not exceed 0.0020%.

The ***nitrogen*** content should be in the range from 0.0020 to 0.0110%. Regulation of the nitrogen content within these limits is necessary for the formation of fine nitrides, carbides or submicroscopic carbonitrides in interaction with titanium, niobium, aluminum or vanadium, which contributes to grain grinding. The minimum nitrogen content should be 0.0020%, and the upper limit should not exceed 0.0110%, in order to avoid the formation of large solid nitrides or titanium carbonitrides larger than 20 microns, which can form at a depth of 1.5 ± 0.5 mm from the surface of the rods intended for the manufacture of springs. This depth is crucial in terms of fatigue stresses. A large number of nitrides or carbonitrides can significantly reduce the fatigue strength of steel at high strength and hardness values.

3. Conclusion

Based on theoretical studies, it has been shown that alloying elements such as carbon, manganese, silicon, chromium, vanadium and nickel play a key role in improving the strength, elasticity and other performance properties of spring steels. Heat treatment, as well as alloying, significantly affects the final properties of materials, especially their hardenability and resistance to decarbonization. The introduction of such elements helps to improve the mechanical properties, increase the wear resistance and durability of spring products.

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